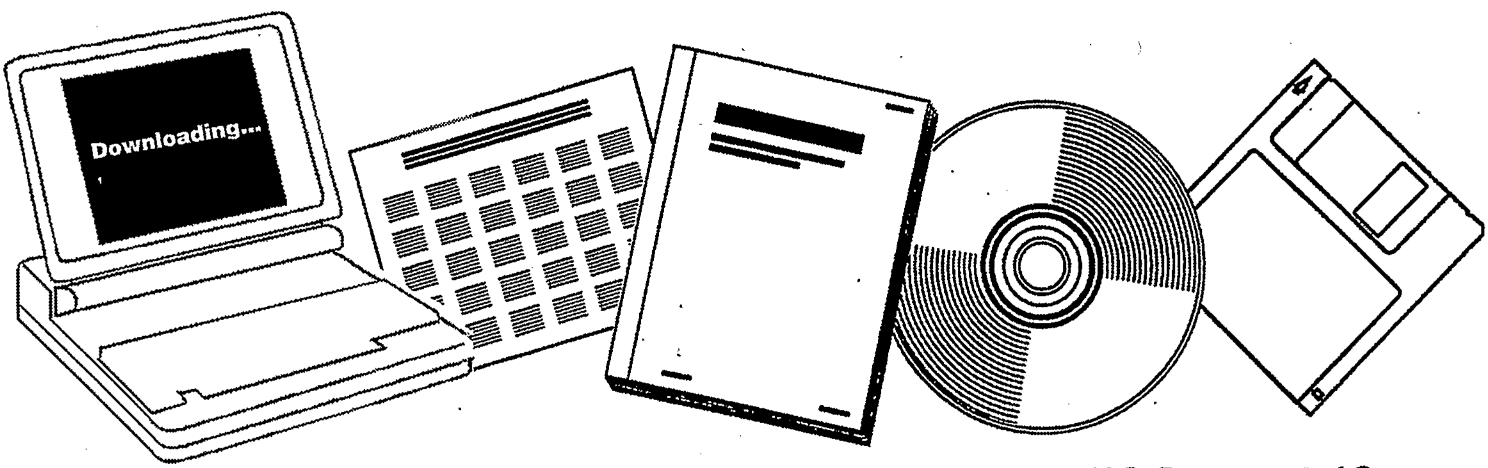
STUDY OF EBULLATED-BED FLUID DYNAMICS FOR H-COAL. QUARTERLY PROGRESS REPORT NO. 6, OCTOBER 1, 1981-DECEMBER 31, 1981

AMOCO RESEARCH CENTER, NAPERVILLE, IL.
RESEARCH AND DEVELOPMENT DEPT

1982



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R. J. SCHAEFER, D. N. RUNDELL

DATE PUBLISHED: FEBRUARY, 1982

CONTRACT DE-AC22-80PC30026

Research and Development Department
Amoco Oil Company
P. O. Box 400
Naperville, Illinois
60566

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R. J. SCHAEFER, D. N. RUNDELL

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PREPARED FOR THE UNITED STATES
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FOREWORD

THE H-Coal process, developed by Hydrocarbon Research, Incorporated, (HRI) involves the direct hydroliquefaction of coal to low-sulfur boiler fuel or synthetic crude oil. The 200-600 ton-per-day H-Coal pilot plant is being operated next to the Ashland Oil, Incorporated, refinery at Catlettsburg, Kentucky, under DOE contract to Ashland Synthetic Fuels, Incorporated. The H-Coal ebullated bed reactor contains at least four discrete components: gas, liquid, catalyst, and unconverted coal and ash. Because of the complexity created by these four components, it is desirable to understand the fluid results of prior cold flow model experiments (1) to the operating H-Coal PDU reactor in Trenton, New Jersey. Studies are also planned to examine the coalescence behavior of gas bubbles in three-phase ebullated beds.

The work to be performed is divided into four parts: fluid dynamics measurements on the PDU reactor, gas bubble coalescence studies at Northwestern University, cold flow and mixing tests at Amoco's Naperville Research Center, and model implementation. The objective of this quarterly progress report is to outline progress in the first two areas.

TABLE OF CONTENTS

SUMMARY

Cold flow fluidization experiments were completed using a 9.8 vol% slurry of coal char in kerosene.

Northwestern University continued development of the holographic and light probe techniques.

INTRODUCTION

The fluid dynamics of the H-Coal reactor has been previously studied in a cold flow unit. Reference 1 provides details of the construction of the unit and results of tests with a variety of gases, liquids, and catalyst sizes. A semi-theoretical model was developed to predict the volume fractions occupied by the gas, liquid, and catalyst phases. The aims of this new contract are fourfold:

1) The model developed using cold flow unit test results will be extended to apply to the operating H-Coal PDU reactor.

2) Because gas bubble dynamics are crucial in determining the nature of the flow, studies of bubble flow will be performed at Northwestern University using optically clear beds.

3) Liquid mixing tests will determine the residence time distribution of liquid in the reactor. Under the previous contract, it was determined that the coal char fines (simulating the unreacted coal and ash) were uniformly distributed throughout the bed. Hence, the measurement of liquid data is essential for modeling the residence time and kinetic parameters associated with the unreacted coal.

4) The model will be implemented into a readily usable format.

DATA COLLECTION

<u>HRI PDU Fluid Dynamics Study</u>
<u>Amoco Cold Flow Fluid Dynamics Tests</u>

Cold flow tests were performed to measure the behavior of a 16.72 wt% (9.8 vol%) coal char/kerosene slurry with nitrogen in fluidizing cylindrical catalyst pellets. Slurry samples were withdrawn from the reactor to verify the coal fines concentration.

<u>Northwestern University</u>
<u>Gas Bubble Dynamics</u>

Experimental efforts continued at Northwestern this period. The new lenses for the holographic system were installed, and a hologram was taken which showed the images of gas bubbles in the fluidized glass bed. Data analysis procedures were developed for the light probe experiments. The requirement for a computerized holographic image analyzer for the holographic experiments was specified, and the construction was started.

Northwestern's monthly progress reports appear in Appendix A.

DATA ANALYSIS

HRI PDU Fluid Dynamics Tests
Amoco Cold Flow Fluid Dynamics Tests

Table I summarizes the measured coal char fines concentration (as determined by millipore filtration) in the kerosene.

Catalyst bed expansions versus liquid and gas velocities are tabulated in Table II. The corresponding data are plotted in Figure 1. At lower liquid velocities ($U_l < 0.120$ ft/sec), some evidence of bed contractions with increasing gas rate is seen.

Dense-phase fluid dynamic variables (gas, liquid, and catalyst holdups, and the Darton-Harrison drift flux, V_{CD}) are tabulated in Table III. The drift flux is plotted versus gas holdup in Figure 2. The solid line represents the ideal bubbly region, while the dashed lines represent system behavior in the transition region between ideal bubbly and churn turbulent. Although there is some scatter in the data, the stabilizing effect of increasing liquid velocity is apparent.

PLANS FOR THE NEXT PERIOD

1) Continue analysis of HRI PDU fluid dynamics tests.

2) Complete a series of cold flow fluid dynamics tests at higher coal char concentration.

3) Continue efforts at Northwestern University.

4) Begin preparations for liquid tracer work.

REFERENCES

1) I. A. Vasalos, et al., Final Progress Report, "Study of Ebullated Bed Fluid Dynamics for H-Coal," Contract DE-AC05-77ET-10149, February, 1980.

NOMENCLATURE		UNITS
ε	Volume fraction of component	
u	Superficial velocity	Ft/Sec
V_{CD}	Darton-Harrison Drift Flux	mm/Sec

<u>Subscripts</u>

b	Bed (dense) phase value
c	Catalyst
g	Gas
l	Liquid
γ	Determined by γ-ray absorption
ΔP	Determined by ΔP measurement

TABLE I

COAL CHAR CONCENTRATIONS IN KEROSENE SLURRY, RUN 222

Sample ID	Sample Location	Wt% Coal Fines
AU-77-169	First spool piece (reactor base)	16.08
AU-77-170	Second spool piece (60" from reactor base)	15.75
AU-77-171	Third spool piece (120" from reactor base)	16.63
AU-77-172	Fourth spool piece (180" from reactor base)	18.43
Average		16.72 ± 1.19

DNR/ml
3/15/82

TABLE II

% BED EXPANSION FOR RUN 222

CATALYST : HDS2A
GAS : NITROGEN
LIQUID : KEROSENE
COAL CHAR CONC: 9.8 VOL %
TEMPERATURE : 72. DEG F

RUN NO.	LIQUID FLOW RATE, FT/SEC	GAS FLOW RATE FT/SEC	CATALYST BED HEIGHT (IN.)	% BED EXPANSION
222- 1	0.049	0.0	49.	17.
- 2	0.074	0.0	53.	26.
- 3	0.096	0.0	58.	38.
- 4	0.121	0.0	64.	52.
- 5	0.144	0.0	73.	74.
- 6	0.167	0.0	89.	112.
- 7	0.049	0.049	49.	17.
- 8	0.072	0.049	54.	29.
- 9	0.088	0.050	66.	57.
-10	0.122	0.051	73.	74.
-11	0.146	0.052	83.	98.
-12	0.171	0.054	97.	131.
-13	0.191	0.054	109.	160.
-14	0.194	0.0	104.	148.
-15	0.047	0.079	47.	12.
-16	0.074	0.077	58.	38.
-17	0.098	0.075	63.	50.
-18	0.122	0.078	76.	81.
-19	0.145	0.080	88.	110.
-20	0.170	0.081	99.	136.
-21	0.195	0.078	114.	171.
-22	0.049	0.107	45.	7.
-23	0.073	0.107	57.	36.
-24	0.097	0.108	63.	50.
-25	0.122	0.109	79.	88.
-26	0.145	0.102	92.	119.
-27	0.168	0.102	103.	145.
-28	0.188	0.102	113.	169.
-29	0.048	0.126	47.	12.
-30	0.073	0.128	58.	38.
-31	0.096	0.131	68.	62.
-32	0.121	0.134	79.	88.
-33	0.132	0.137	94.	124.
-34	0.049	0.149	49.	17.
-35	0.073	0.153	59.	40.
-36	0.098	0.157	69.	64.
-37	0.097	0.104	69.	64.
-38	0.050	0.046	49.	17.
-39	0.122	0.117	79.	88.
-40	0.120	0.155	74.	76.
-41	0.144	0.160	93.	121.
-42	0.171	0.166	110.	162.

TABLE II

% BED EXPANSION FOR RUN 222
-2-

CATALYST : HDS2A
GAS : NITROGEN
LIQUID : KEROSENE
COAL CHAR CONC: 9.8 VOL %
TEMPERATURE : 72. DEG F

RUN NO.	LIQUID FLOW RATE, FT/SEC	GAS FLOW RATE FT/SEC	CATALYST BED HEIGHT (IN.)	% BED EXPANSION
222-43	0.169	0.127	107.	155.
-44	0.049	0.178	47.	12.
-45	0.074	0.185	58.	38.
-46	0.099	0.186	65.	55.
-47	0.121	0.186	74.	76.
-48	0.146	0.179	93.	121.
-49	0.169	0.187	113.	169.
-50	0.049	0.218	45.	7.
-51	0.073	0.213	58.	38.
-52	0.098	0.224	64.	52.
-53	0.049	0.050	49.	17.
-54	0.075	0.178	56.	33.
-55	0.098	0.183	67.	60.
-56	0.116	0.217	66.	57.

TABLE III

CALCULATED HOLDUPS, RUN 222: DENSE PHASE

CATALYST : HDS2A
GAS : NITROGEN
LIQUID : KEROSENE
COAL CHAR CONC: 9.8 VOL %
TEMPERATURE : 72. DEG F

RUN NO.	LIQUID FLOW RATE, FT/SEC	GAS FLOW RATE, FT/SEC	ε_{cs}	$\varepsilon_{\ell,\gamma}$	$\varepsilon_{\ell,\Delta P}$	ε_{gb}	VCD (MM/SEC)
222- 1	0.049	0.0	0.47	0.47	0.51	0.0	0.0
- 2	0.074	0.0	0.44	0.49	0.53	0.0	0.0
- 3	0.096	0.0	0.40	0.54	0.56	0.0	0.0
- 4	0.121	0.0	0.36	0.61	0.60	0.0	0.0
- 5	0.144	0.0	0.32	0.62	0.63	0.0	0.0
- 6	0.167	0.0	0.26	0.65	0.66	0.0	0.0
- 7	0.049	0.049	0.47	0.44	0.0	0.04	12.9
- 8	0.072	0.049	0.43	0.45	0.0	0.07	10.8
- 9	0.088	0.050	0.35	0.53	0.51	0.06	11.5
-10	0.122	0.051	0.32	0.55	0.55	0.07	10.5
-11	0.146	0.052	0.28	0.59	0.59	0.07	10.4
-12	0.171	0.054	0.24	0.62	0.64	0.08	9.6
-13	0.191	0.054	0.21	0.64	0.68	0.08	9.6
-14	0.194	0.0	0.22	0.71	0.68	0.0	0.0
-15	0.047	0.079	0.49	0.40	0.0	0.07	20.4
-16	0.074	0.077	0.40	0.46	0.0	0.09	17.8
-17	0.098	0.075	0.37	0.46	0.47	0.12	14.2
-18	0.122	0.078	0.30	0.52	0.54	0.12	13.8
-19	0.145	0.080	0.26	0.56	0.58	0.11	14.6
-20	0.170	0.081	0.23	0.61	0.63	0.09	16.0
-21	0.195	0.078	0.20	0.63	0.67	0.10	13.7
-22	0.049	0.107	0.51	0.35	0.0	0.10	25.9
-23	0.073	0.107	0.41	0.44	0.0	0.11	24.8
-24	0.097	0.108	0.37	0.43	0.42	0.15	20.0
-25	0.122	0.109	0.29	0.51	0.51	0.14	21.0
-26	0.145	0.102	0.25	0.55	0.57	0.14	18.0
-27	0.168	0.102	0.22	0.58	0.60	0.13	17.8
-28	0.188	0.102	0.20	0.61	0.63	0.12	18.0
-29	0.048	0.126	0.49	0.37	0.0	0.10	31.4
-30	0.073	0.128	0.40	0.45	0.0	0.11	30.6
-31	0.096	0.131	0.34	0.46	0.47	0.15	26.3
-32	0.121	0.134	0.29	0.48	0.49	0.18	23.5
-33	0.132	0.137	0.25	0.54	0.50	0.16	26.4
-34	0.049	0.149	0.47	0.42	0.0	0.07	40.6
-35	0.073	0.153	0.39	0.45	0.0	0.11	37.2
-36	0.098	0.157	0.34	0.47	0.48	0.15	33.6
-37	0.097	0.104	0.34	0.48	0.48	0.13	21.2
-38	0.050	0.046	0.47	0.43	0.0	0.05	11.7
-39	0.122	0.117	0.29	0.49	0.53	0.16	20.5
-40	0.120	0.155	0.31	0.46	0.49	0.18	28.2
-41	0.144	0.160	0.25	0.51	0.55	0.19	27.8
-42	0.171	0.165	0.21	0.55	0.59	0.18	28.5
-43	0.169	0.127	0.22	0.54	0.62	0.18	18.9
-44	0.049	0.178	0.49	0.36	0.0	0.11	44.7

TABLE III

CALCULATED HOLDUPS, RUN 222: DENSE PHASE
-2-

CATALYST : HDS2A
GAS : NITROGEN
LIQUID : KEROSENE
COAL CHAR CONC: 9.8 VOL %
TEMPERATURE : 72. DEG F

RUN NO.	LIQUID FLOW RATE, FT/SEC	GAS FLOW RATE, FT/SEC	ε_{cB}	$\varepsilon_{\ell,\gamma}$	$\varepsilon_{\ell,\Delta P}$	ε_{gb}	VCD (MM/SEC)
222-45	0.074	0.185	0.40	0.43	0.0	0.12	44.7
-46	0.099	0.186	0.36	0.45	0.49	0.14	41.2
-47	0.121	0.186	0.31	0.46	0.48	0.18	35.0
-48	0.146	0.179	0.25	0.50	0.52	0.20	31.3
-49	0.169	0.187	0.20	0.54	0.56	0.19	32.3
-50	0.049	0.218	0.51	0.32	0.0	0.13	52.7
-51	0.073	0.213	0.40	0.43	0.0	0.13	51.6
-52	0.098	0.224	0.36	0.44	0.46	0.15	50.7
-53	0.049	0.050	0.47	0.43	0.0	0.05	13.0
-54	0.075	0.178	0.41	0.43	0.0	0.11	43.1
-55	0.098	0.183	0.35	0.47	0.51	0.14	41.3
-56	0.116	0.217	0.35	0.41	0.45	0.19	41.7

Figure 1

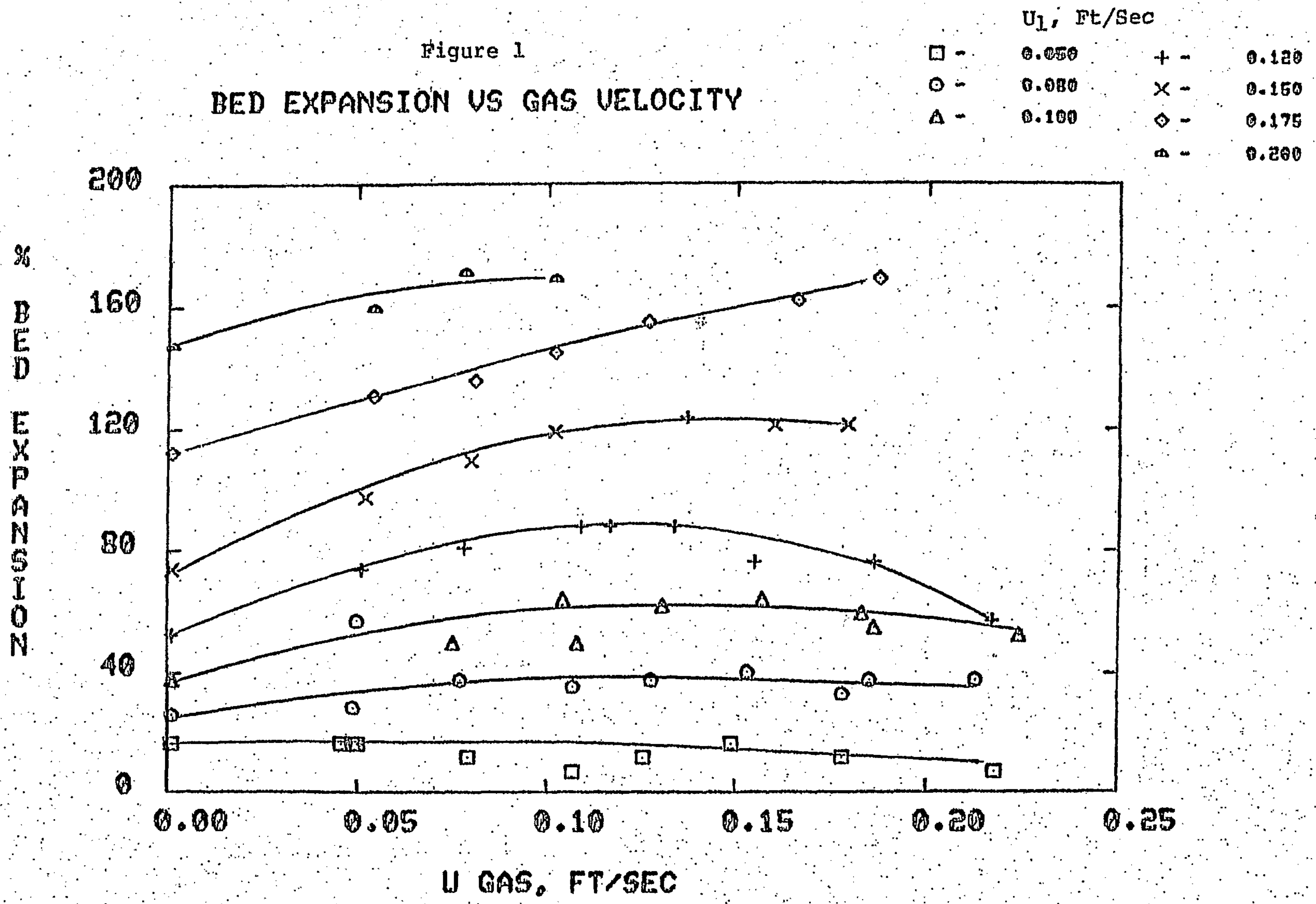
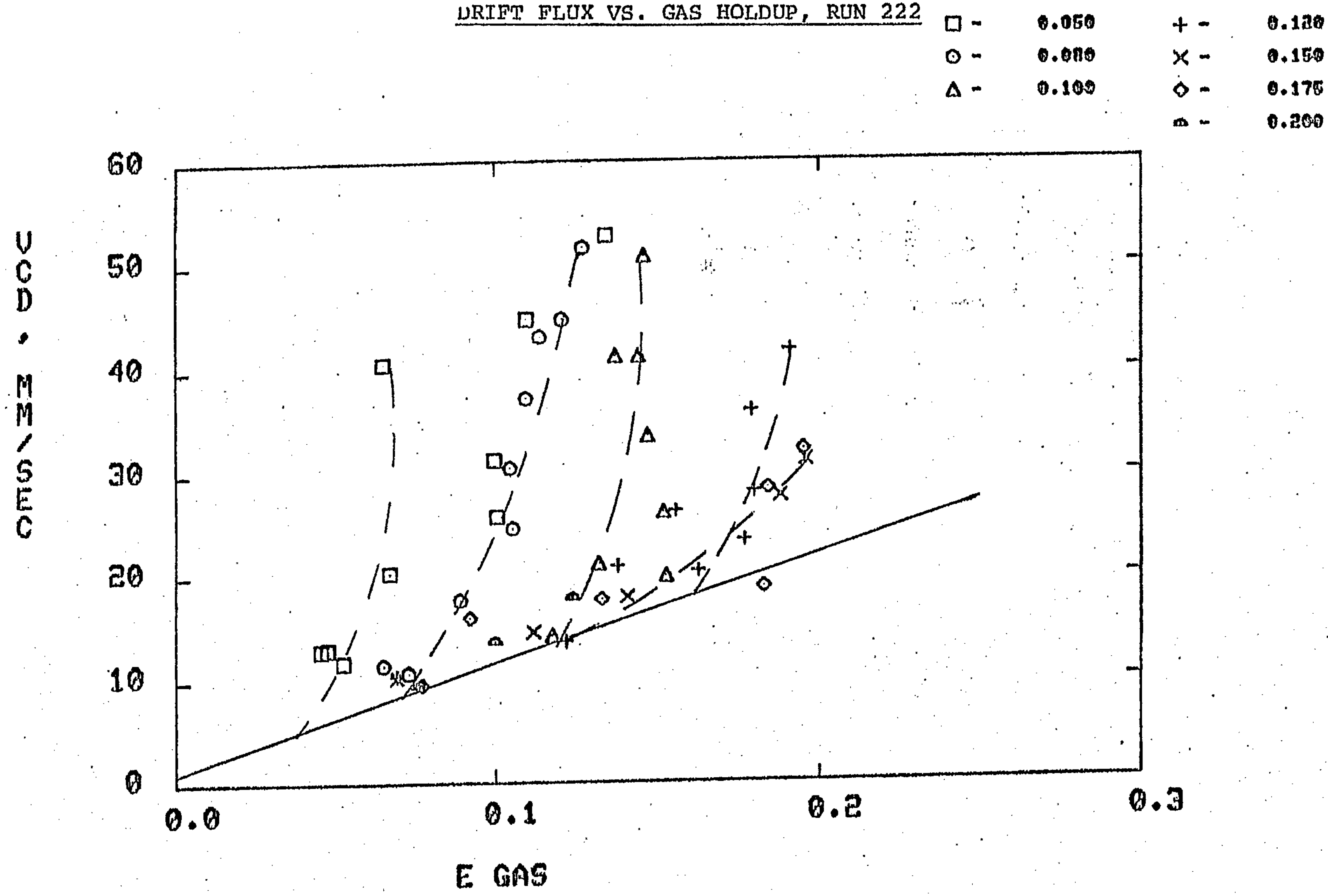

BED EXPANSION VS GAS VELOCITY
U_l, Ft/Sec
□ - 0.050
○ - 0.080
△ - 0.100
+ - 0.120
× - 0.150
◇ - 0.175
⌂ - 0.200
% BED EXPANSION
200
160
120
80
40
0
0.00
0.05
0.10
0.15
0.20
0.25
U GAS, FT/SEC

Figure 2

DRIFT FLUX VS. GAS HOLDUP, RUN 222



APPENDIX A

NORTHWESTERN UNIVERSITY MONTHLY PROGRESS REPORTS

MONTHLY (OCTOBER 1981) PROGRESS REPORT ON AMOCO DOE CONTRACT "ON H-COAL FLUID DYNAMICS"

I. Light Beam Probe

A) Small Bubble Analysis

The analysis procedure and computer routines necessary for the reduction of data from small (0.06 mm to 0.2 mm diameter) bubbles are now essentially complete. The routines have been checked out using numerically simulated data and our next step will be to test them using data generated from latex particles having a known size distribution. A small gravity driven flow apparatus to circulate the latex particles through the light beam is now being assembled. A description of the analysis method has been written up and following the test with the latex particles, it will be put in final form and made available to AMOCO.

B) Large Bubble Analysis

A more refined statistical analysis procedure is being worked out for the data collected from large bubbles (0.2 mm to about 4 mm diameters). It is basically the same procedure as was written up before, but with the addition of routines to smooth out statistical fluctuations in the accumulated data before it is analyzed.

II. Holography

A new lens has been mounted in the holographic imaging equipment which will allow images to be formed totally behind the holographic plate. This will provide an unobstructed view of the holographic image during reconstruction.

After installation of the new lens and calibration, the first hologram was taken through the fluidized glass bed. The depth of field of the developed hologram was small, but distinct bubbles were observed. These bubbles were small (on the order of 0.2 mm) and generally non-spherical.

A holographic image analysis system is currently being developed. It will make use of the already existing video camera/monitor system used to view reconstructed holograms. An electronic system is being devised which will place a bright vertical and horizontal line on the monitor screen. These lines will be movable by the analyst and their positions on the screen will be given as a 12-bit binary word. By interfacing this to a computer it will be possible to calculate bubble diameters from their holographic images. Currently, the electronic components are being ordered for this system.

III. Conductivity Probe

The results from conductivity probe measurements, which were included in a previous report, show the variation of void fraction with respect to radial position, and both gas and liquid flow rates. Unfortunately, due to the limitations on the instrument, the dependency of void fraction on those parameters can be shown only qualitatively not quantitatively.

It is noted that at a constant liquid flow rate, the void fraction distribution across the column is more symmetric at higher gas flow rates. This means less channeling occurs in the bed as the gas flow rate is increased. Also, it is found that a more uniform distribution of bubbles can be achieved at higher liquid flow rates.

Fig. 1 and Fig. 2 shows the output signal from the probe as the bed is fluidized. Once the probe is within the bed, it is no longer possible to distinguish the liquid phase from the gas phase. Obviously further work with the probe is meaningless.

It is suggested to use an A-C probe instead of the D-C probe, and to increase the conductivity of the liquid if it is possible. A sensor of non-negligible length may be useful according to the studies of Hoffer et al (1975). They used a modified probe for the measurements in fine dispersions. The average drop diameter was 0.1 - 0.3 mm in their experiment. However, the calibration work of the probe was tedious. Also, it seems unnecessary to use the probe technique since it appears that better measurements can be taken by using a laser.

Reference:

Hoffer, M. S. and Resnick, W. " A Modified Electroresistivity Probe Technique for Steady- and Unsteady-State Measurements in Fine Dispersions." Chem. Eng. Sci. Vol. 30, pp. 473-521, 1975.

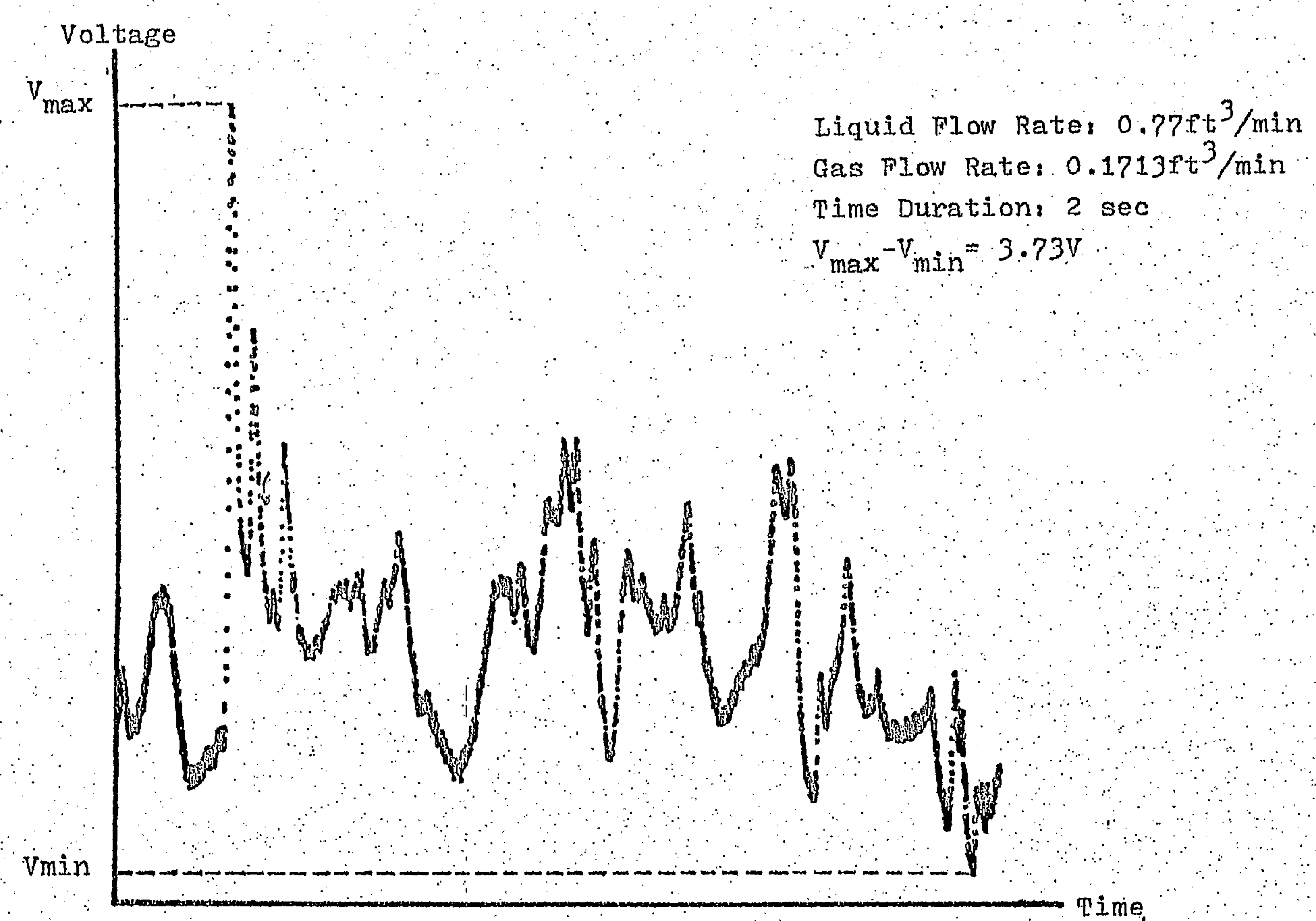
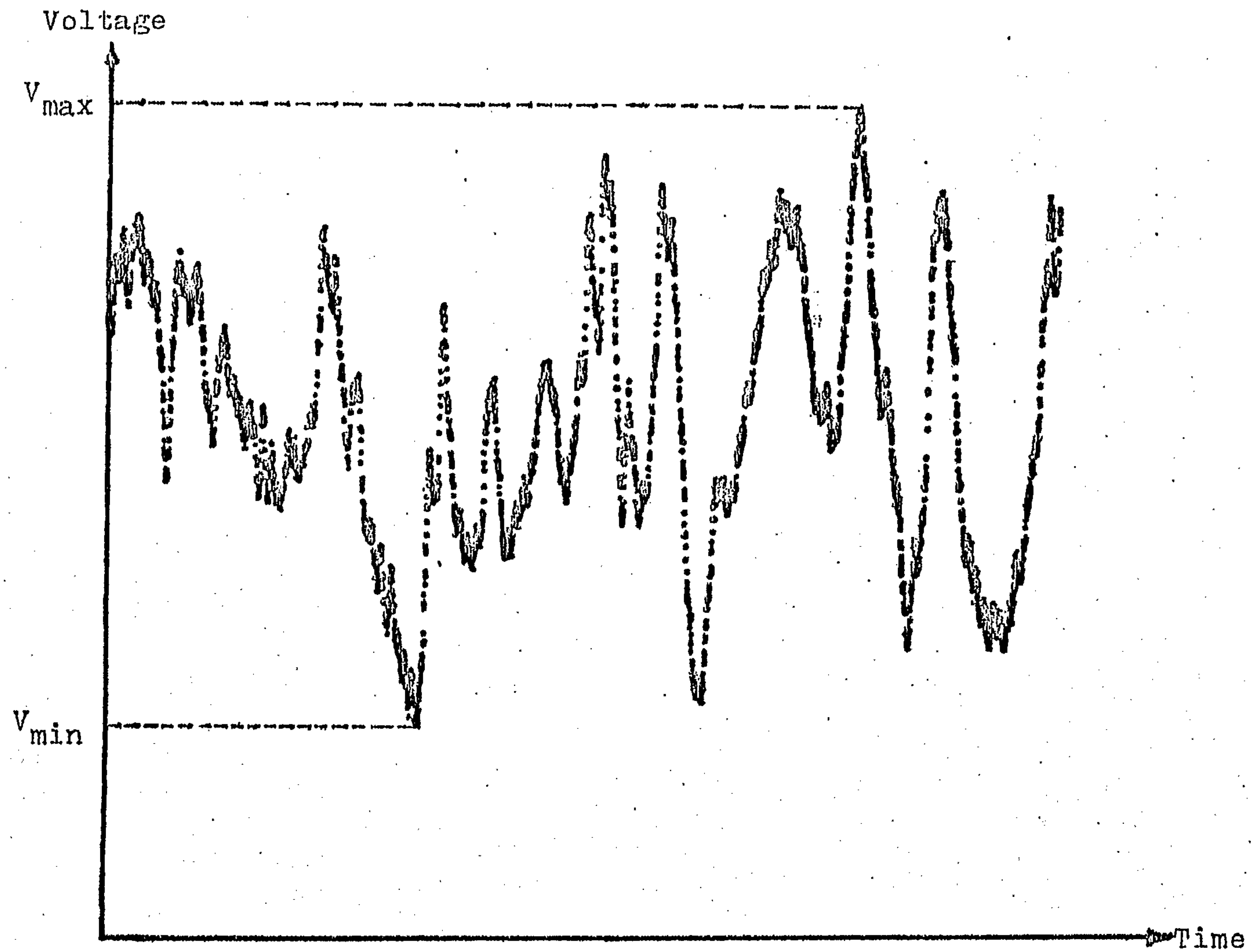


Fig.1 Typical output signal from the probe.
The bed is fluidized but the probe is above the bed.



Liquid Flow Rate: 1.25ft/min
Gas Flow Rate: 0.1713ft/min
Time Duration: 2 sec
$V_{max}-V_{min}= 2.07$ V

Fig. 2 Typical signal from the probe if the probe is <u>within</u> the fluidized bed.

MONTHLY (DECEMBER 1981) PROGRESS REPORT ON AMOCO DOE CONTRACT

"ON H-COAL FLUID DYNAMICS"

I. Light Beam Probe

The work on the Light Probe portion of the project during the month of December was a continuation of the effort begun in November to organize and describe the data analysis procedures. Ideas and assumptions that were somewhat shadowy before are, as a result, becoming more clearly defined. In addition, more refined methods of accomplishing certain tasks, such as data smoothing, are being incorporated into the procedures.

II. Holography

The design of a holographic image analysis system is now complete, along with partial construction and testing. This system is designed to view the hologram on a video screen and, by placing movable "crosshairs" at desired locations, calculate image sizes. Distances are calculated on the video screen by obtaining digital representation of the x and y positions and storing these into a computer.

At this time the video "crosshairs" system has been assembled and is working properly. It is now possible to move a thin horizontal and vertical line anywhere on the screen. These lines are superimposed on the normal video image and are controlled by means of keyboard switches representing "up", "down", "right", and "left." It is also possible to adjust the speed at which the lines move.

Parts are now being ordered to complete the system. These include a cable to run data to the department's PDP 11/44 computer and assorted electronic components necessary for data transfer.

It is hoped that upon arrival of this additional equipment the image analysis system will be completed within a month.

MONTHLY (NOVEMBER 1981) PROGRESS REPORT ON AMOCO DOE CONTRACT "ON H-COAL FLUID DYNAMICS"

I. Light Beam Probe

The development of our analysis procedures for the light beam data is now nearly complete. Two significant improvements have been made and they are:

1. A refinement of our original large bubble analysis procedure which extends its range of applicability to bubbles with radii down to approximately the beam radius (80 μm). The previous lower limit was about three times the beam radius.
2. The addition of routines to do "least square" fits of smooth, but otherwise arbitrarily shaped curves to the size and velocity distribution data. The degree of imposed "smoothness" can be specified.

Our current efforts are to consolidate the progress we have made over the past few months and put into a coherent package both the ideas involved and the numerous computer routines necessary to implement the ideas.

II. Holography

It has been determined that a more sophisticated method of hologram analysis is needed in order to speed up data acquisition, thereby making this research technique more attractive. It is felt that the simplest and most inexpensive device would be one which eliminates the need for hard-copy photos which focus upon different planes in the reconstructed hologram. Since a video camera and monitor are available, such a device would only have to be capable of making measurements on the video screen and transfer these to a computer. Such a device has been designed and is partially constructed, which, hopefully, will display a horizontal and vertical line on the video monitor, superimposed upon the focused image of some plane in the hologram. The positions of these lines will be manually controlled and fed into a computer. Thus, the researcher can determine the x and y positions of a point on the surface of a bubble and, by recording several such points, can calculate the diameter of the bubble.

Currently, the basic circuit has been built and the next step is to construct signal conditioning circuits for the video output and for the horizontal and vertical sync pulses. Also the question of just how to interface the 12-bit digital words, which contain the x and y positions, with a computer must be resolved.

III. Resistivity Probe

A topical report on the use of resistivity probe is being prepared.